

Effects of Black Carbon and Other Non-Kyoto Pollutants on Climate

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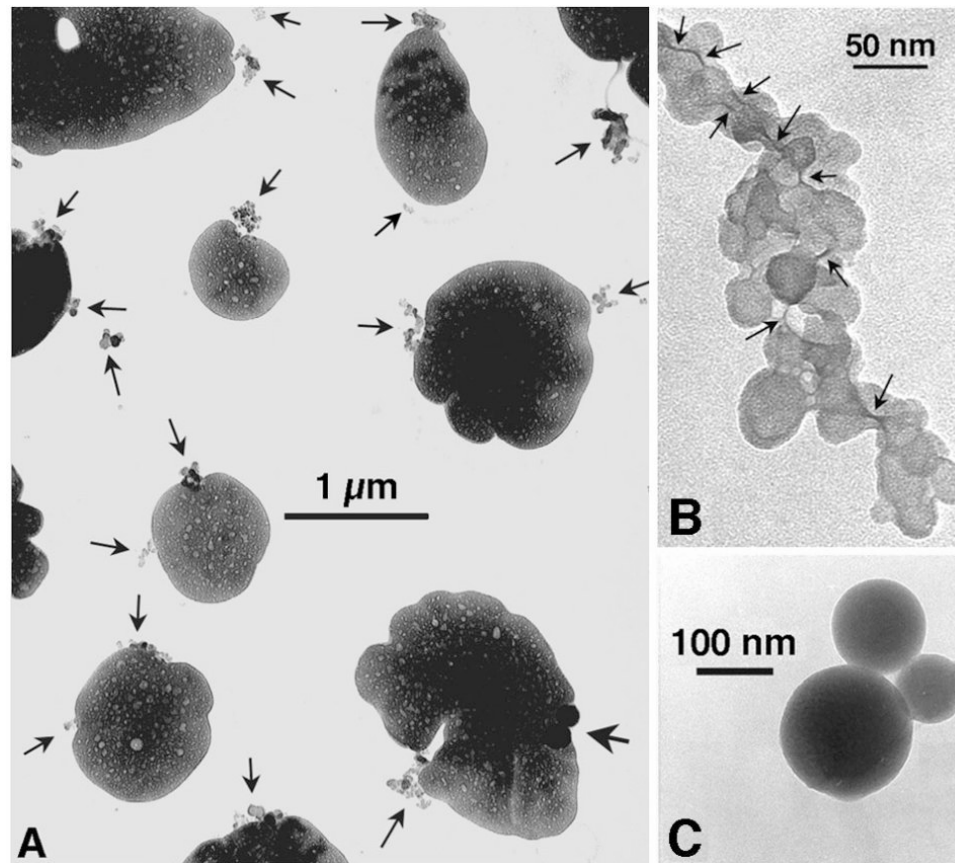
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Regional Black Carbon Effects

- Aerosol clouds over Los Angeles containing black carbon increased daytime atmospheric heating rates by > 0.5 K/hr and reduced solar radiation to the ground by over 6% (e.g., regional dimming), causing net warming of the basin over two days in 1987. Jacobson (1997) (Atm. Env. 31, 587)
- “Atmospheric brown clouds...contribute to atmospheric solar heating and surface cooling...and...contribute as much as the recent increase in anthropogenic greenhouse gases to regional lower atmospheric warming trends.” Ramanathan et al. (2007) (Nature 448, 575)

Fractal Soot Agglomerates (Arrows) Coated by Ammonium Sulfate



Pósfai et al. (1999)

Global Black Carbon Effects

- Direct radiative forcing due to internally-mixed black carbon of $> 0.5 \text{ W/m}^2$. Jacobson (Jan. 2000) (GRL, 27, 217).
- Direct forcing due to black carbon of 0.5 W/m^2 . Hansen (Aug. 2000) (PNAS, 97, 9875).
- Direct forcing due to black carbon ($0.5\text{-}0.8 \text{ W/m}^2$) Chung and Seinfeld (2002) (JGR 107, D19)
- Black carbon may be second leading cause of global warming in terms of climate response. “Reducing black carbon plus organic matter will not only slow global warming but also improve human health” Jacobson (2001-pub. 2002) (JGR 107, D19)
- Results unfortunately used as basis for the U.S. pulling out of the Kyoto Protocol: “The Kyoto Protocol was fatally flawed...Kyoto also failed to address two major pollutants that have an impact on warming, black soot and tropospheric ozone. Reducing both would not only address climate change but also dramatically improve people’s health.” Bush (2001) NYT (6/12/01)
- “The U.S. will spend \$1.7 billion in FY’03 for basic research on climate change, \$40 million of which is dedicated to leverage other funding to address major gaps in understanding the carbon cycle and the role of black soot. U.S. Climate Change Research Initiative (2002).

Positive Global Direct Forcing (W/m^2)

Anthropogenic Greenhouse Gases (IPCC, 2007)

Carbon Dioxide	+1.66 (~48%)
Methane	+0.48 (~14%)
Nitrous oxide	+0.16 (~4.6%)
Halocarbons	+0.34 (~9.7%)
CFCs*	+0.268
HCFCs*	+0.039
HFCs+PFCs+SF6	+0.017
Ozone (trop and strat)*	+0.30 (~8.6%)
Total gases	+2.94 (~84%)

Anthropogenic aerosol particles (Nature 409, 695, 2001)

Black carbon*	+0.55 (~16%)
Total	+3.49

*non-Kyoto chemicals (33.2% of total direct forcing)

California Emissions

Kyoto gases	Percent contribution to Kyoto gases	
	World	California (2004)
Carbon Dioxide	71.6	83.8
Methane	20.7	5.7
Nitrous oxide	6.9	6.8
HFCs+PFCs+SF6	0.73	2.9

Percent global warming due to Kyoto Gases 66.4%

Global CO₂ from California: 6.5% (492 Tg-C / 7600 Tg-C)

Global BC+OM (FF+BF) from California: 1.5% (0.25 Tg-C/ 17.1 Tg-C)

Percent warming of BC relative to CO₂ 33% 7.6%

Percent warming of CH₄ relative to CO₂ 29% 6.8%

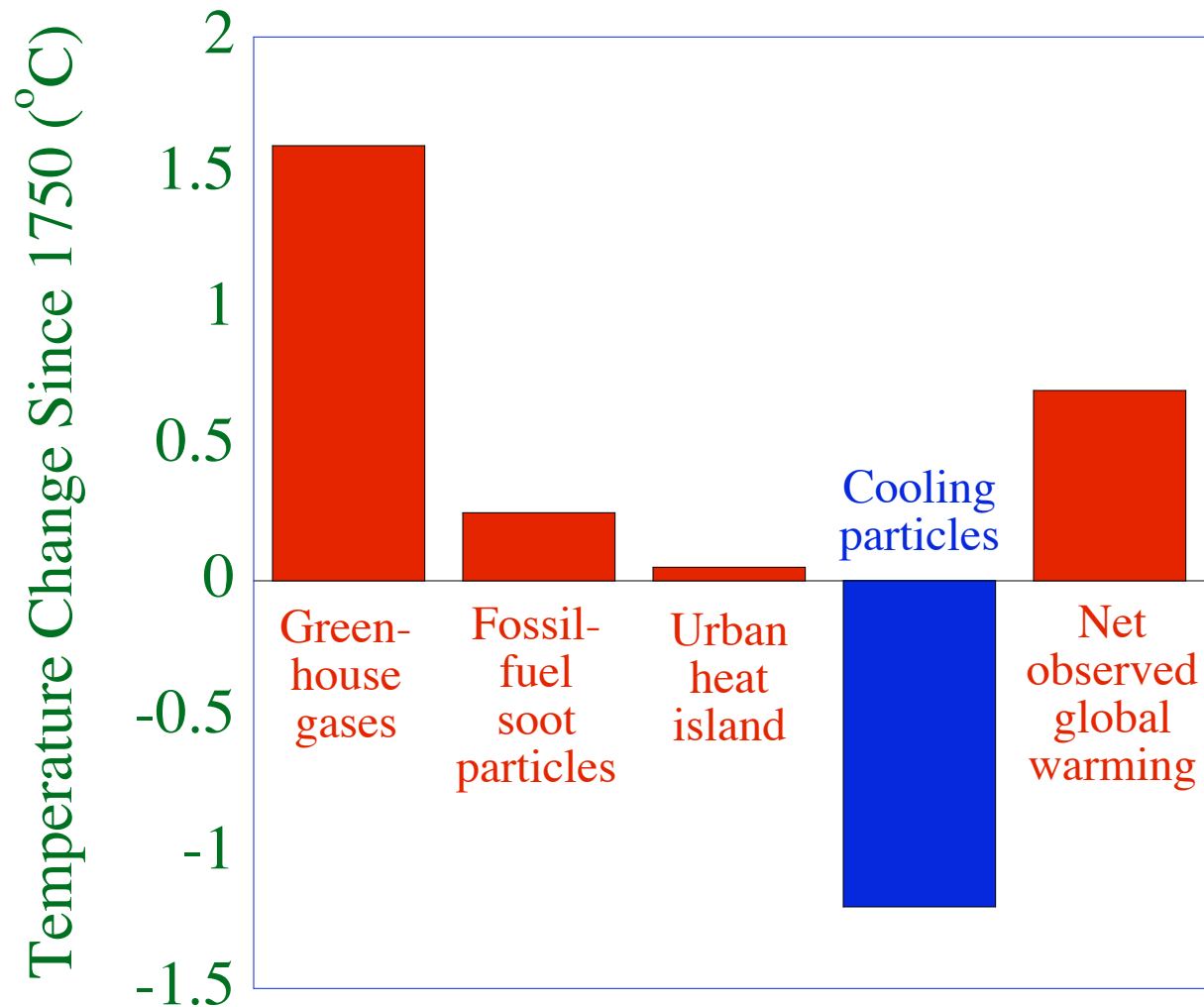
Percent warming of N₂O relative to CO₂ 9.6% 8.1%

Sources of California BC

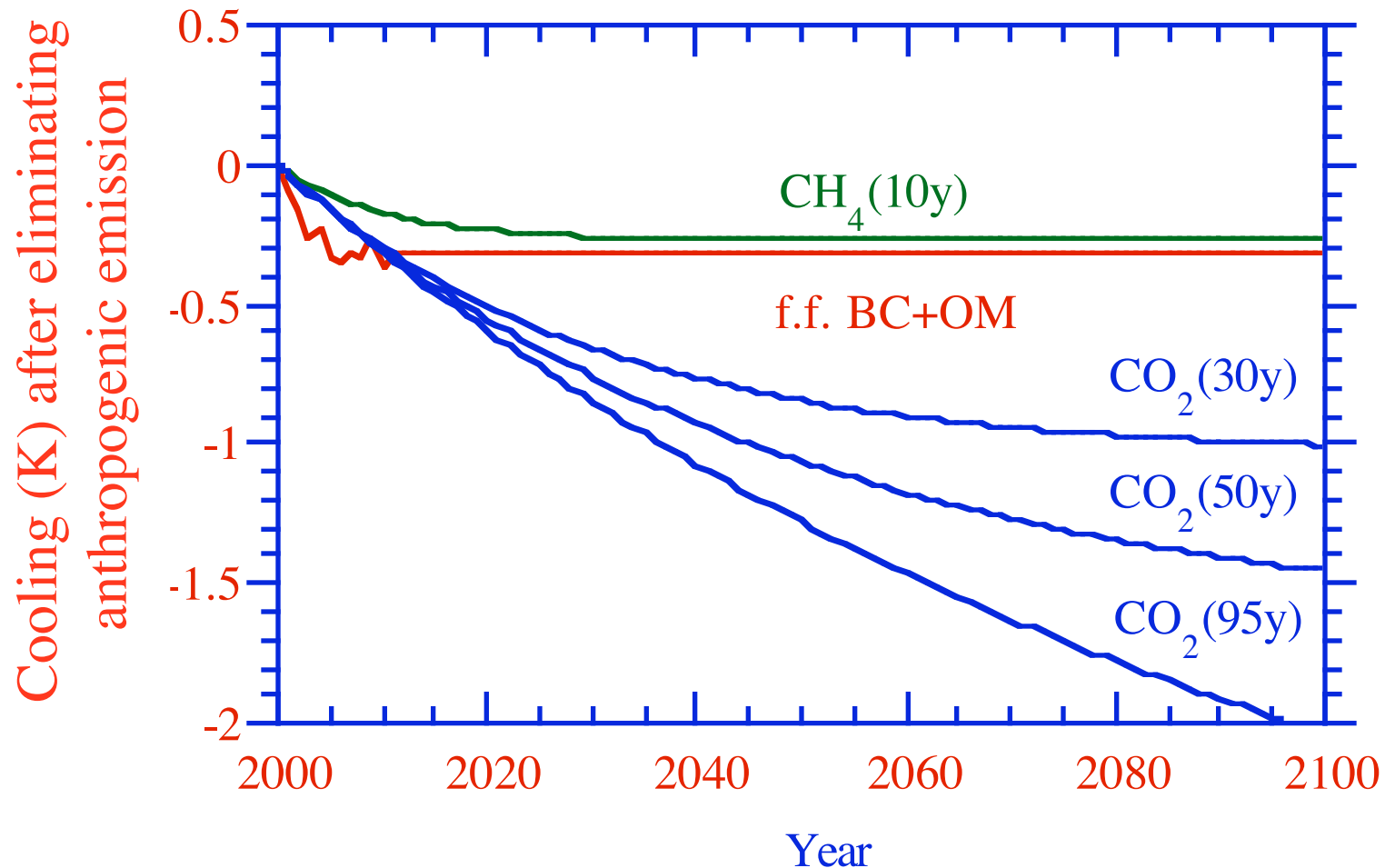
Mobile (13.5%); Nonroad (32.84%); Area (51.4%); Stack (1.08%); Fug (1.26%)

IPCC (2007), CEC (2006) USEPA (2006), Bond et al. (2004)

Causes of Global Warming



Global Temperature Changes Due to Eliminating Anthropogenic CO₂, CH₄, f.f. BC+OM (Soot) Emissions



Soot, BC Global Warming Potential

X	20-year GWP	100-year GWP
FF soot*	2530	840 - 1280
BC in FF soot	4470	1500 - 2240

GWP = Change in temperature per unit emissions of X relative to the change in temperature per unit emissions of CO₂

Multiply by 12/44 for GWP relative to CO₂-C

*FF soot = 56% BC + 43% POC + 1% sulfate

California's Vehicle Strategy

Current regulation of California fuel types can have only uncertain effects on climate and air quality due to uncertainties in lifecycle emission modeling, variation of emissions among vehicles, and overly simplistic treatments in 99% of atmospheric models.

For example, a strategy of regulating ozone-forming gases (NO_x and HCs simultaneously) may reduce ozone and soot (enhancing cooling) but reduce cooling particles more, causing net warming without changing CO₂ much.

On the other hand, a strategy that eliminates combustion entirely in favor of electric vehicles and hydrogen fuel cell vehicles powered by wind/solar/hydro/geothermal will result in both air pollution and climate benefits.

To illustrate, the U.S. can replace all onroad vehicles with battery-electrics powered by 71,000-122,000 5 MW turbines, eliminating vehicle CO₂, soot and cooling particles, and ozone-precursors, causing net cooling and improving health.

Lifecycle CO₂-Equivalent Emissions Accounting for Black Carbon

Delucchi (2006)* Accounts for

- climate impacts of BC, other PM, NO, CO (not in GREET)
- detailed nitrogen cycle (GREET accounts for only some N terms)
- changes in prod/consump due to price changes (not in GREET)
- C-cycle of land-use change (simplistic in GREET - 2 parameters)
- biogeophysical impacts of landuse change (not in GREET)

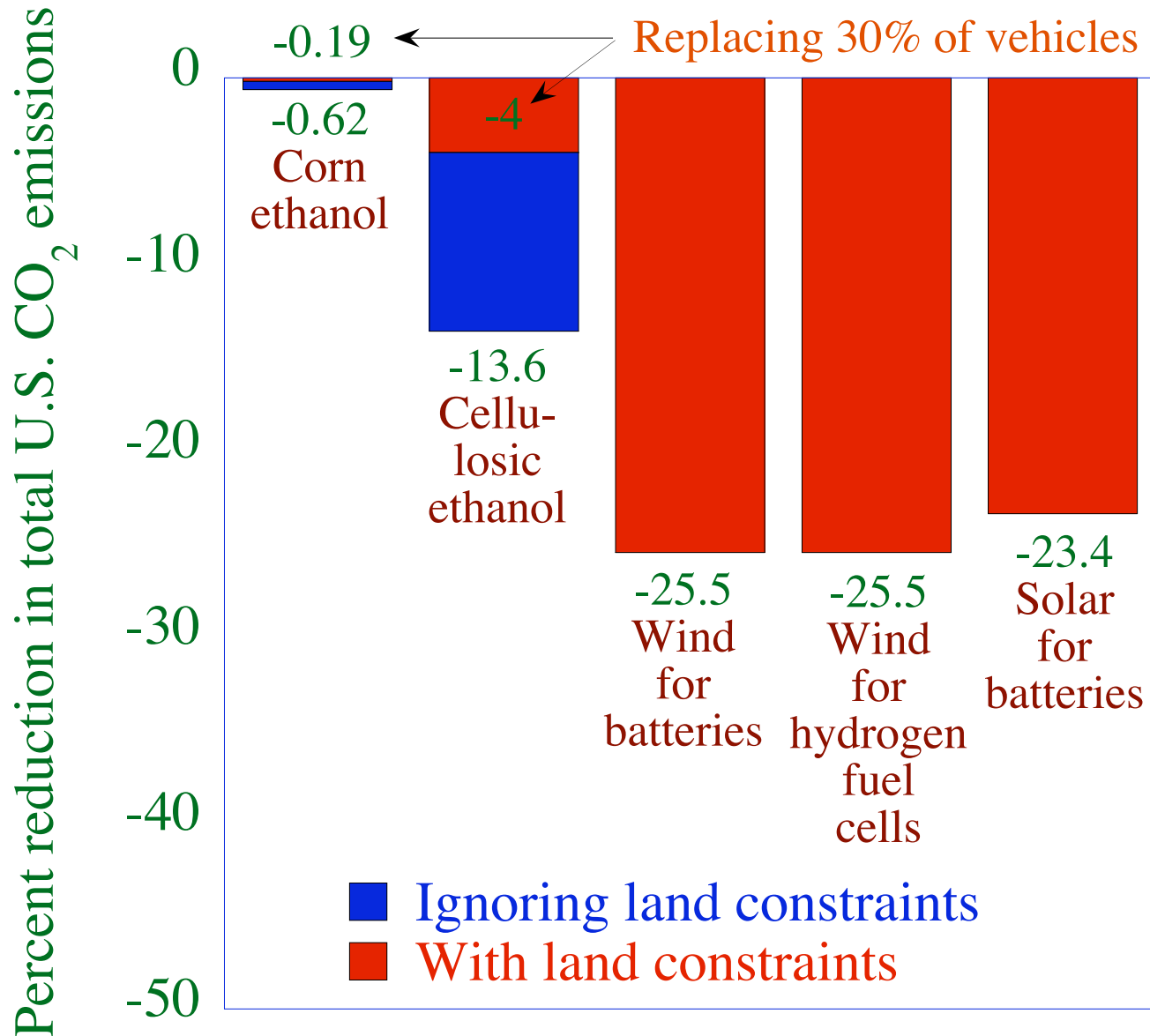
U.S. corn ethanol ~2.4% less CO₂-eq. emis. than light-duty gasoline
(China +17%; India +11%; Japan +1%, Chile -6%)

Switchgrass ethanol projected 52.5% less CO₂-eq. emis. than LDG -

Soy biodiesel ~50% more CO₂-eq. emis. than heavy-duty diesel
Mostly due to fuel, feedstock, fertilizer production/cultivation

*www.its.ucdavis.edu/publications/2006/UCD-ITS-RR-06-08.pdf

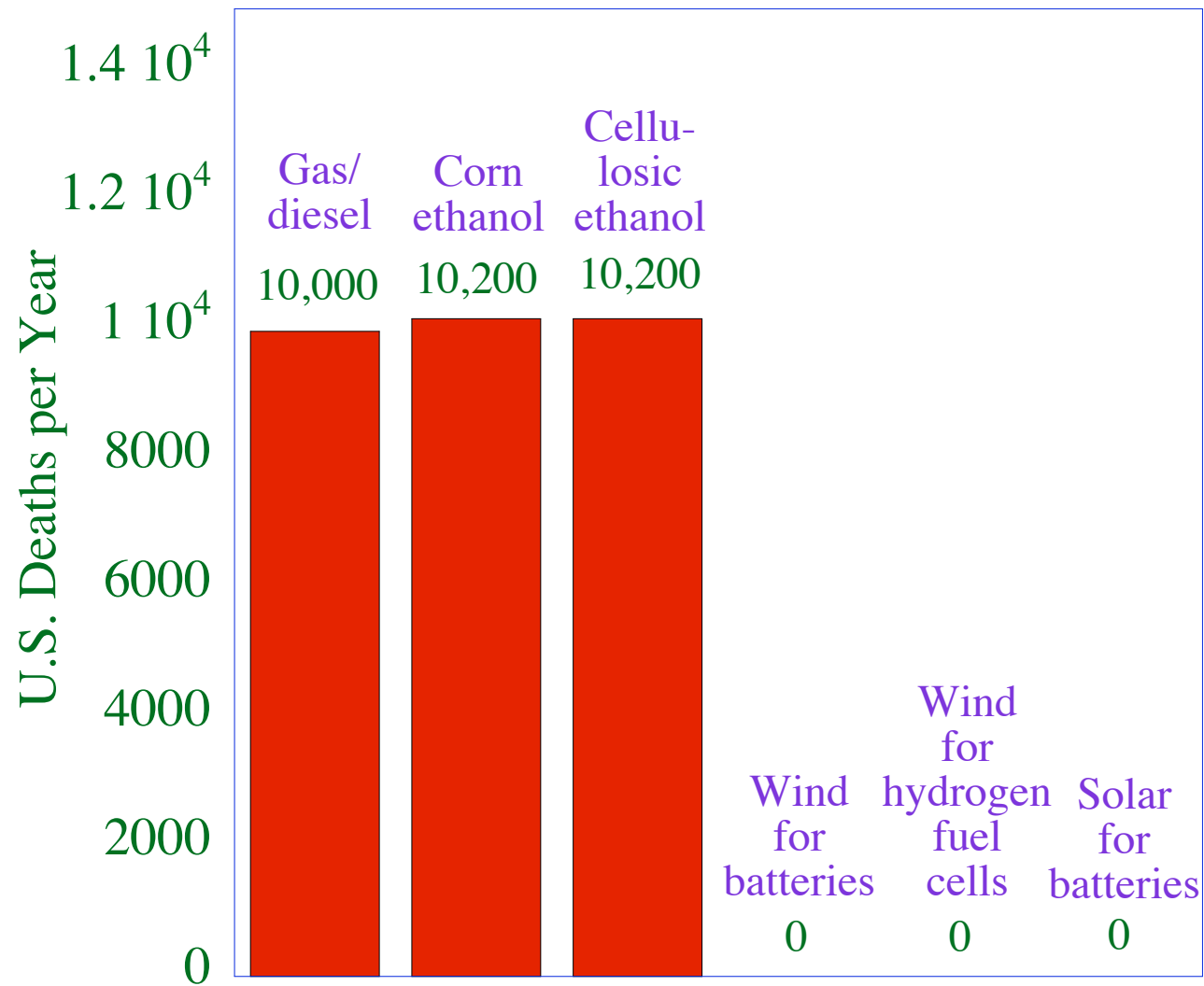
Percent Decrease in Total U.S. Carbon Dioxide Upon Replacing 100% of Onroad Vehicles



Area to Power 100% of U.S. Onroad Vehicles



Future U.S. Deaths Per Year From Onroad Vehicle Emissions



Summary

Non-Kyoto pollutants account for about 33% of warming attributable to all pollutants globally, with soot (black carbon + organic matter + small sulfate) accounting for almost half of this.

In California, the ratio of FF+BF soot to CO₂ emissions is lower than on the global scale, but warming from California FF+BF soot is roughly equivalent to that from each CH₄ and N₂O.

Current emission regulations will not eliminate FF+BF soot, thus California has room to obtain further climate and health benefits from regulating soot as a global-warming agent, spurring other states and countries to reduce soot as well.

Further regulation of ozone-forming gases (both NO_x and HCs simultaneously) will reduce ozone and cooling particles, causing an uncertain climate impact, but a certain health benefit. However, when vehicle CO₂ emissions are reduced as well, the climate benefit becomes more apparent. Ozone-precursor, soot, and CO₂ emission reductions can be obtained most efficiently with mandatory increases in electric and hydrogen fuel cell vehicles powered by wind/solar/hydro/geothermal.

For example, the U.S. can replace all onroad vehicles with battery-electrics powered by 71,000-122,000 5 MW turbines, eliminating vehicle CO₂, soot, and ozone-precursors.